Tracked Vehicle – Soft Soil Interactions and Design Sensitivities for Path Clearing Systems Utilizing Multi-Body Dynamics Simulation Methods

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Overview

Objective: compare multiple path clearing vehicle designs in the medium unmanned vehicle category (~800 kg)

- Introduction and mobility events
- Design alternatives
- Soft soil theory
- Modeling methodology
- Design Comparison
- Sensitivity Study
- Conclusion

Comparative Study Introduction

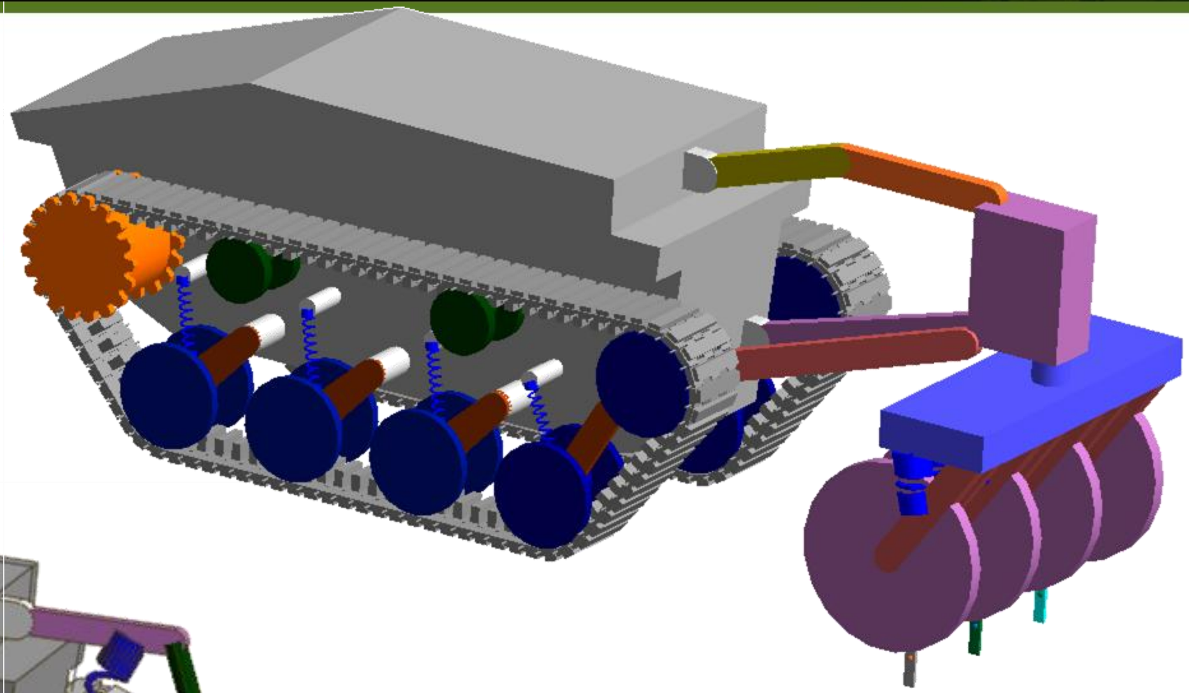
- Path clearing design comparative objective
- Performance study of possible vehicle configurations
  - 2 or 4 road wheels per side
  - Segmented track or band track
  - Flail or roller-rake path clearing implement.
- Soft soil mobility events conducted over clay and sand:
  - Half-round bump: 17.5 cm radius
  - Pot hole: 17 cm deep x 60 cm long
  - V-ditch: 1.4 m deep x 7.8 m long
  - Grades: 40%-60%
  - Cross-country (clay only)

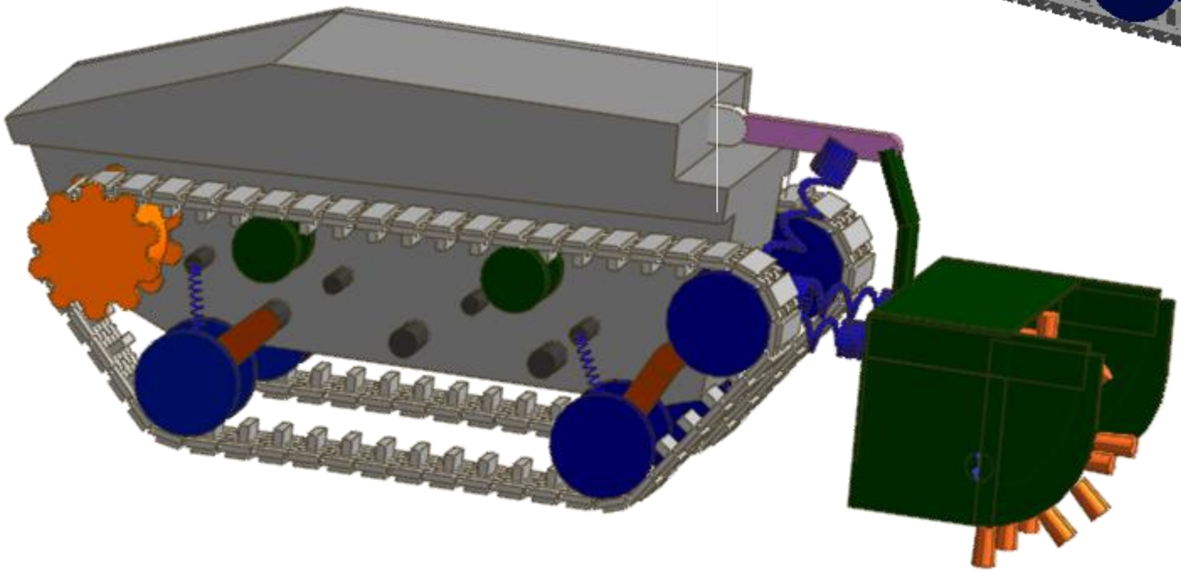
Vehicle Dynamics Application

- Combination of soft soil terramechanics, vehicle dynamics, and Multi-Body Simulation (MBD) code
  - Soft soil models supported within MBD code for tire-soil and track-soil interactions
  - Soft soil models not supported within MBD for rake-soil or flail-soil interactions
  - Custom algorithms / user-defined functions (UDF) needed
- Used code does not support band tracks
  - Modeled as a multitude of small segments

Design Configurations

- Eight configurations designed and tuned for comparison
- All eight configurations were tested over ten events each





- Top figure – 4 road wheels per side, roller-rake, band track
- Bottom figure – 2 road wheels per side, flail, segmented track

Track Suspension Design

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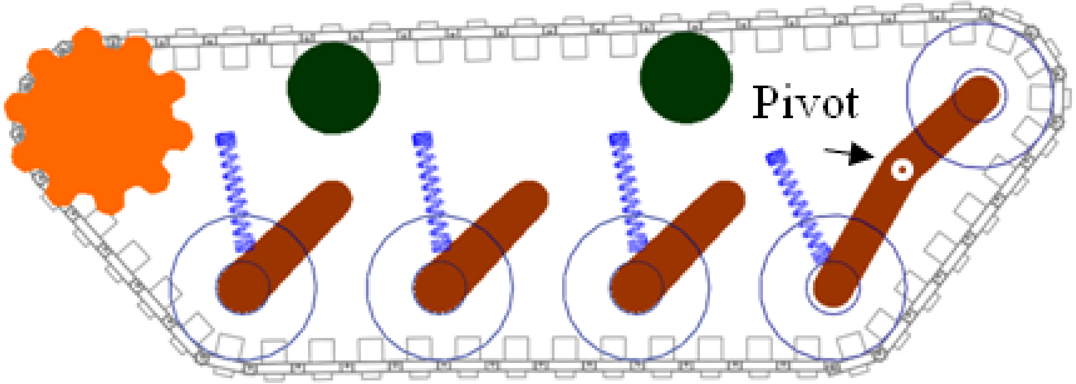
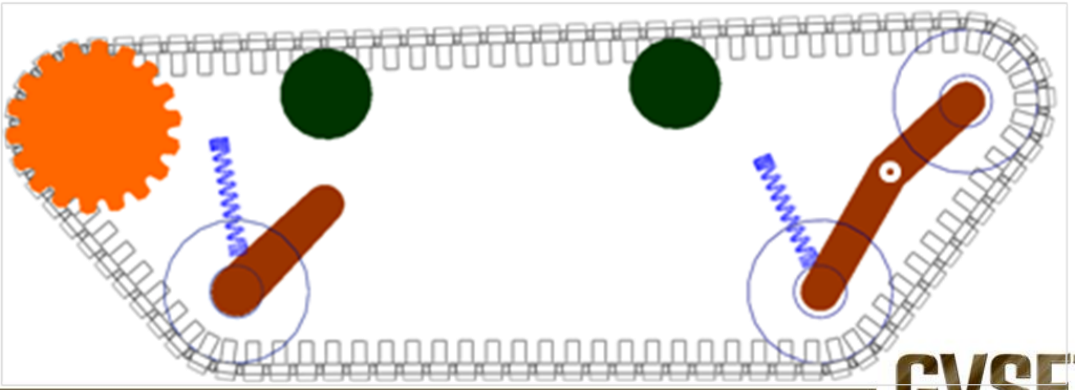
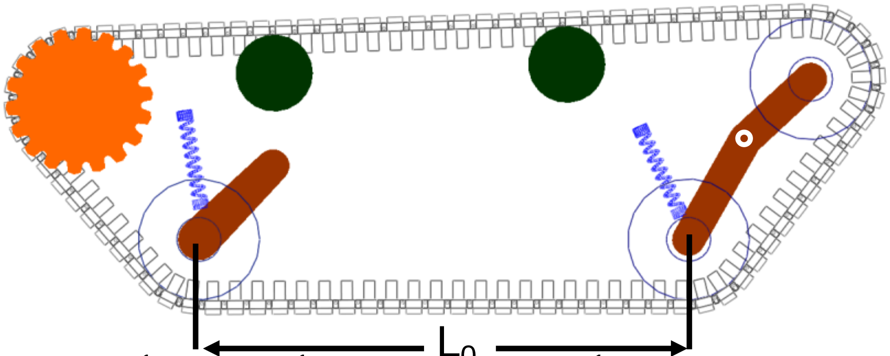
- Two road wheels allow for simpler design; mass and cost savings
- Four road wheels allow for lower ground pressure





Track Design: Band Track vs. Segmented Track

- Material stiffness measured as multiple equivalent springs:
  - 90 segments
  - Hookes Law
  - Young's Modulus
  - E = 47 MPa: K = 5618 kN/m



$$F_m = \frac{E * A_0 * \Delta L}{L_0}$$

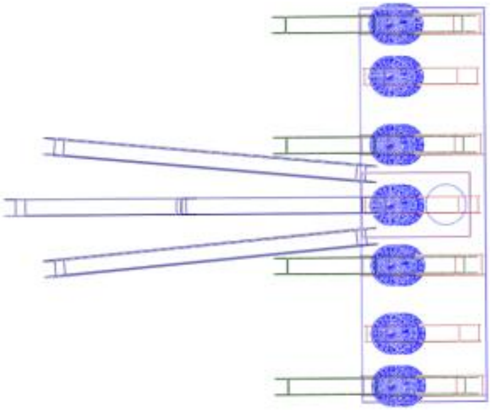
K_{eq}

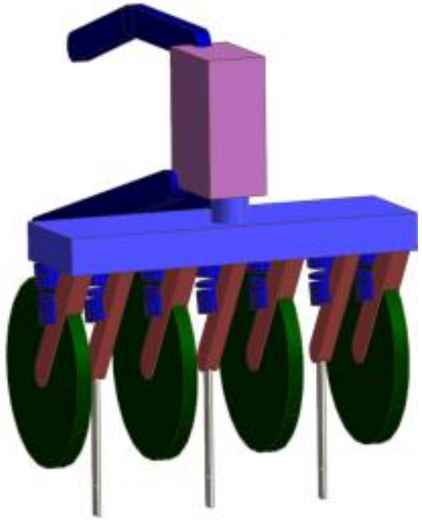
$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \cdots + \frac{1}{K_n} = \frac{n}{K}$$

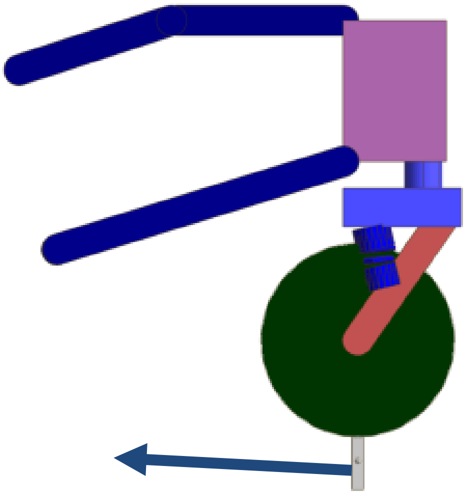
- Segmented track:
  - 50 segments, Default bushing stiffness

Path Clearing Implement: Rake

- 4 rollers; 3 rake blades
- Trailing-arm suspension
- 13 cm max penetration depth
  - Penetration depth is dependent on terrain's resistance







Path Clearing Implement: Flail

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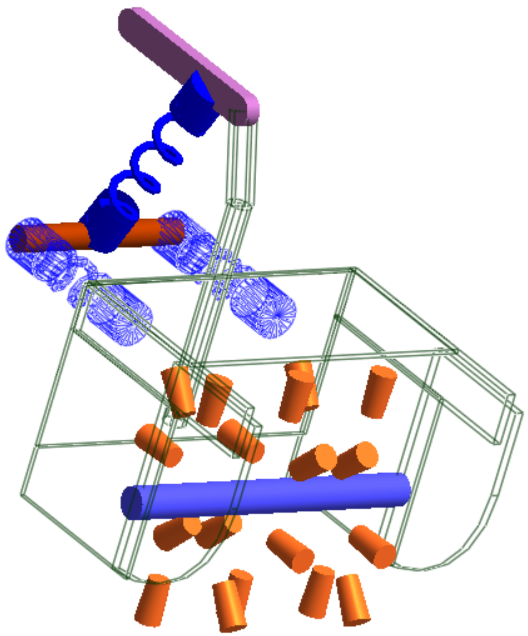
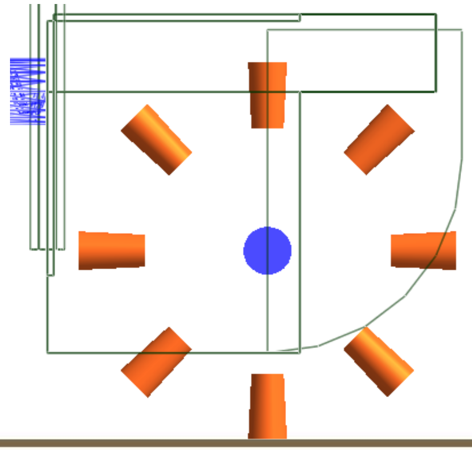
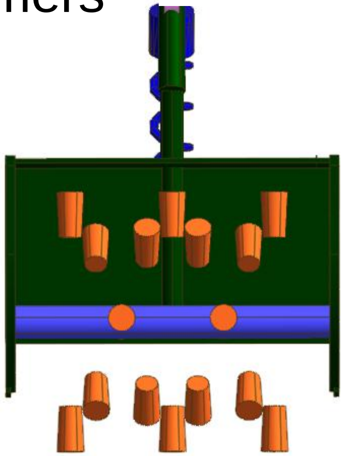
- Flail consists of 9 pairs of rapidly rotating hammers
- Hammer pairs counterbalance
  - 180° offset
- Impact regions of hammer pairs overlap
  - 45° offset between neighboring hammers

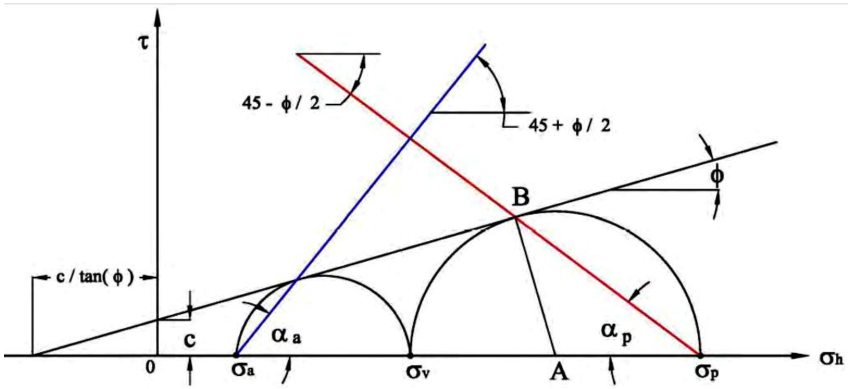






Soft Soil Theory – Mohr-Coulomb

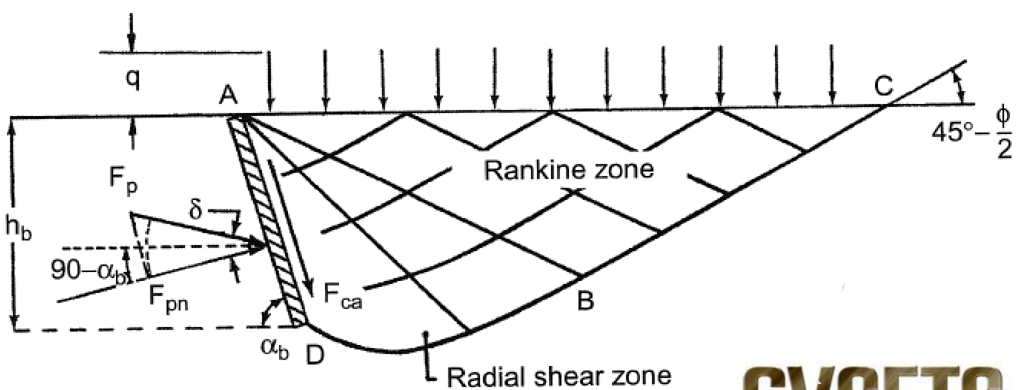
$$\tau_{max} = c + \sigma \tan\varphi$$



$$N_\varphi = \tan^2(45° + \varphi/2)$$

$$\sigma_p = \gamma_s z N_\varphi + q N_\varphi + 2c\sqrt{N_\varphi}$$

Soil Property	Sand	Clay
Exponent Number (n) []	1.1	0.13
Terrain Stiffness (k_C) [kN/m^{1+n}]	0.99	12.7
Terrain Stiffness (k_φ) [kN/m^{2+n}]	1528	1556
Cohesion (c) [kN/m^2]	1.04	68.95
Shear Resistance Angle (φ) [rad]	0.70	0.35
Soil Flow Value (N_φ) []	4.60	2.04
Soil Specifc Gravity (γ) [N/m^3]	14.91	11.77
Blade-Terrain Interface Friction (δ) [rad]	14.91	11.77



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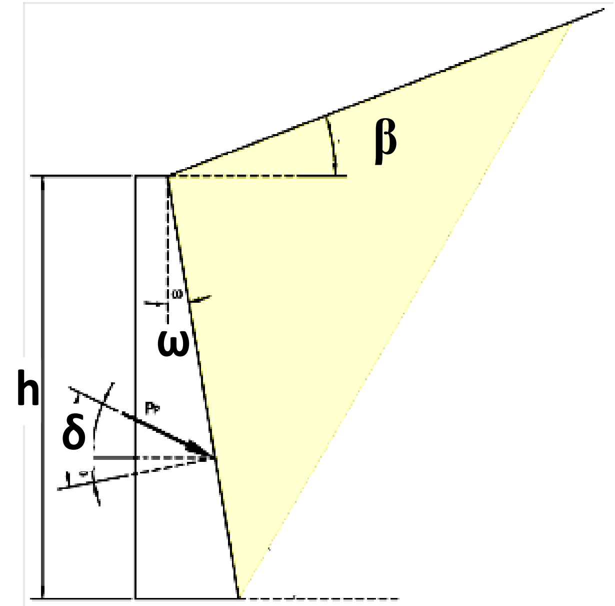
Soft Soil Theory – Coulomb Theory

$$K_p = \frac{\cos^2(\varphi+\omega)}{\cos^2(\omega)*\cos(\delta-\omega)\left[1-\sqrt{\frac{\sin(\delta+\varphi)*\sin(\varphi+\beta)}{\cos(\delta-\omega)*\cos(\beta-\omega)}}\right]^2}$$

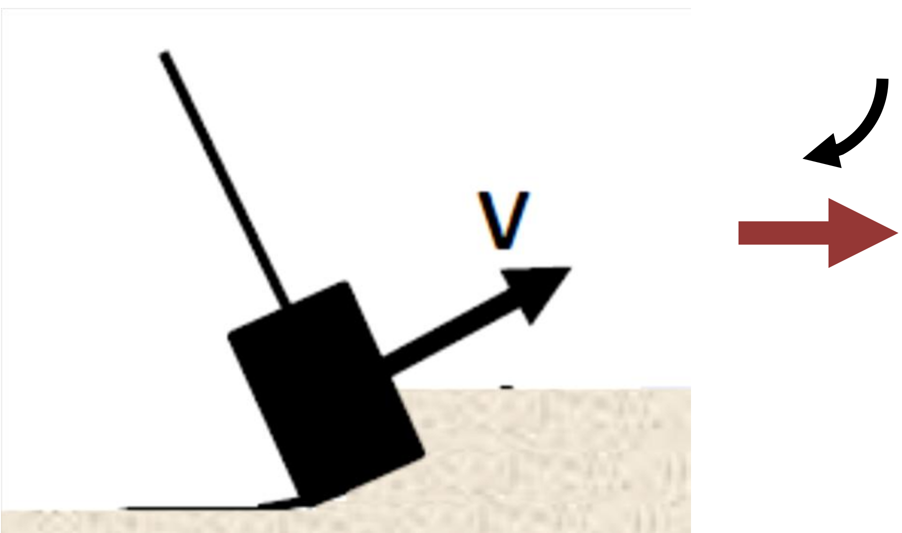


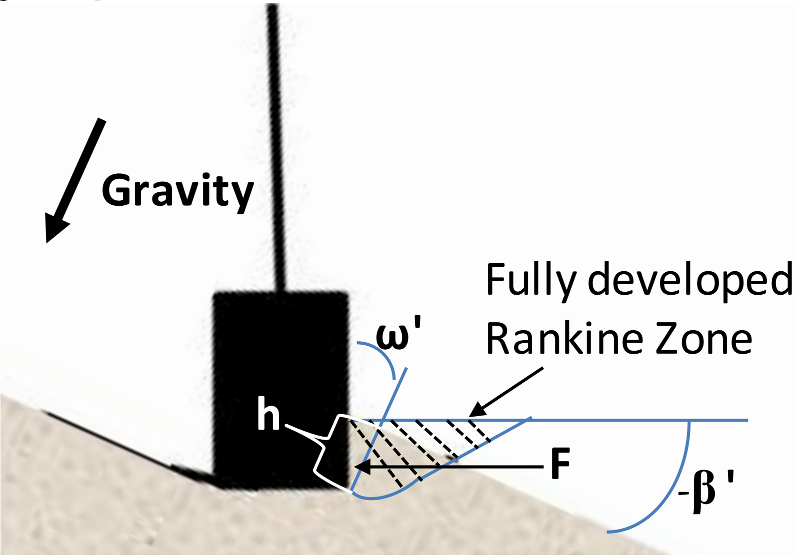
- K_p replaces N_φ; accounts for more conditions
- Assumptions of Coulomb Theory:
  - Pure horizontal motion
  - Soil resistance zone is fully developed (Rankine Zone)
- Suitable model for rake blade – terrain interaction
- Must be modified for flail hammer – terrain interaction
- Terzaghi's Bearing Pressure equation used for resultant force

$$F_p = b*(0.5\gamma_s h_b^2 K_p + q h_b K_p + 2c h_b \sqrt{K_p})$$

Soft Soil Theory – Flail and Coulomb Theory

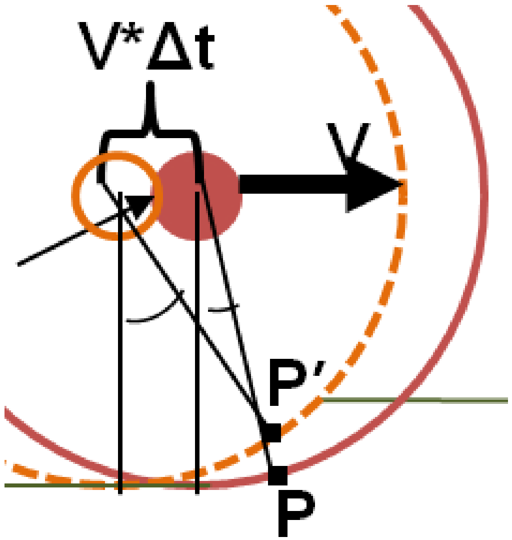
- Flail hammers rotate in an arc
- Internal resistance of soil must develop to resist the direction of motion
- Reimagined Coulomb Theory's passive failure model

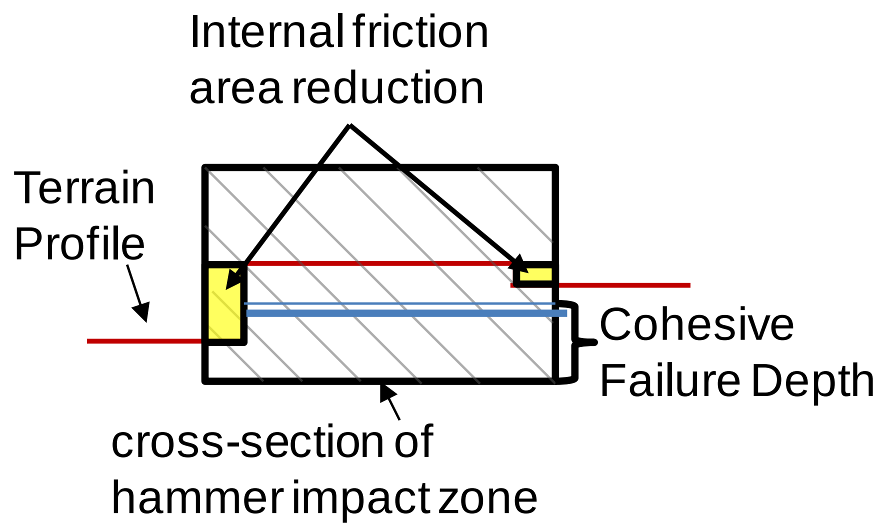




- *ω', β'* substituted into Coulomb Theory's equation for K_p
- Impact forces not modeled

Modified Depth Calculation of Counterbalancing Hammer Pairs



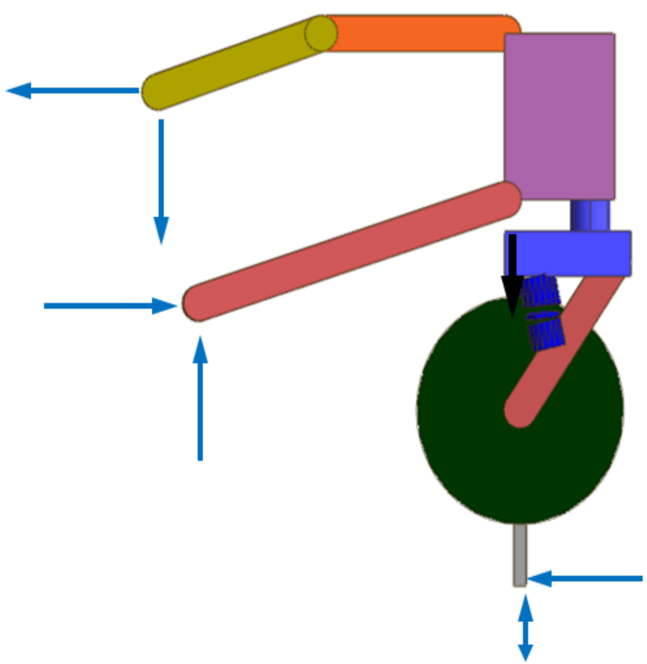


- Counterbalancing hammer, *P'*, may have previously cleared the terrain at current impact location, *P*

- Neighboring hammers have overlapping clearance areas

Roller Rake Loads over Sand vs. Clay

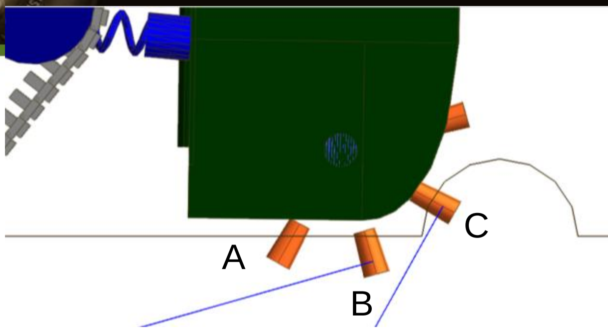
- Two-dimensional force breakdown – 2 m/s, flat soft-soil terrain

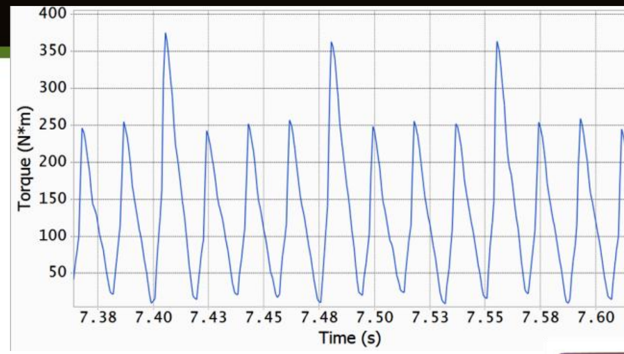


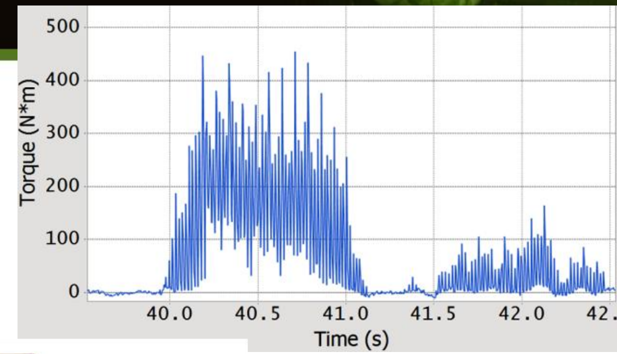
Load Location	**Sum of Forces: +X Direction (lbs)**	
	Sand	Clay
Combined Lower Interface Brackets	984	3329
Upper Interface Bracket	-863	-2392
Rolling Resistance	-51	-55
Blade Horizontal Force	-71	-899
Summation	**-1**	**-17**

Load Location	**Sum of Forces: +Y Direction (lbs)**	
	Sand	**Clay**
Combined Lower Interface Brackets	385	1078
Upper Interface Bracket	-33	-336
Wheel Normal Force	3348	2868
Blade Vertical Force	6	80
Weight	-3686	-3686
Summation	**20**	**4**

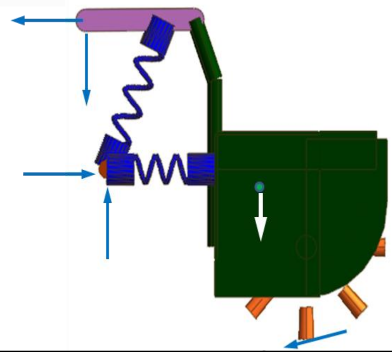
Flail Loads over Sand vs. Clay







- Two-dimensional force breakdown
  – 2 m/s, flat soft-soil terrain



Load Location	Sum of Forces: +X Direction (lbs) Sand	Sum of Forces: +X Direction (lbs) Clay
Combined Lower Interface Brackets	1768	3017
Upper Interface Bracket	-1757	-2550
Hammer Impact Horizontal Force	-16	-469
Summation	**-5**	**-2**

Load Location	Sum of Forces: +Y Direction (lbs) Sand	Sum of Forces: +Y Direction (lbs) Clay
Combined Lower Interface Brackets	2153	2046
Upper Interface Bracket	-671	-414
Hammer Impact Vertical Force	-2	-164
Weight	-1472	-1472
Summation	**8**	-4

Performance of 2 vs. 4 Road Wheels Per Side

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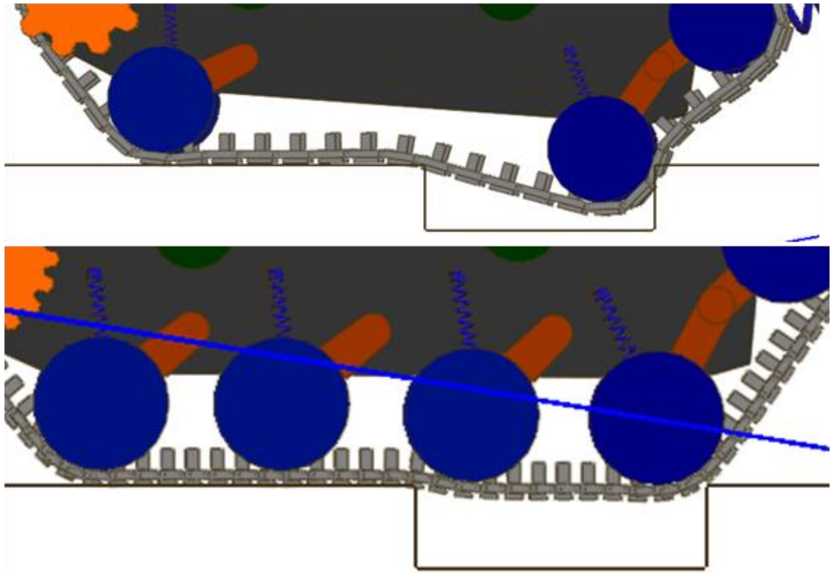
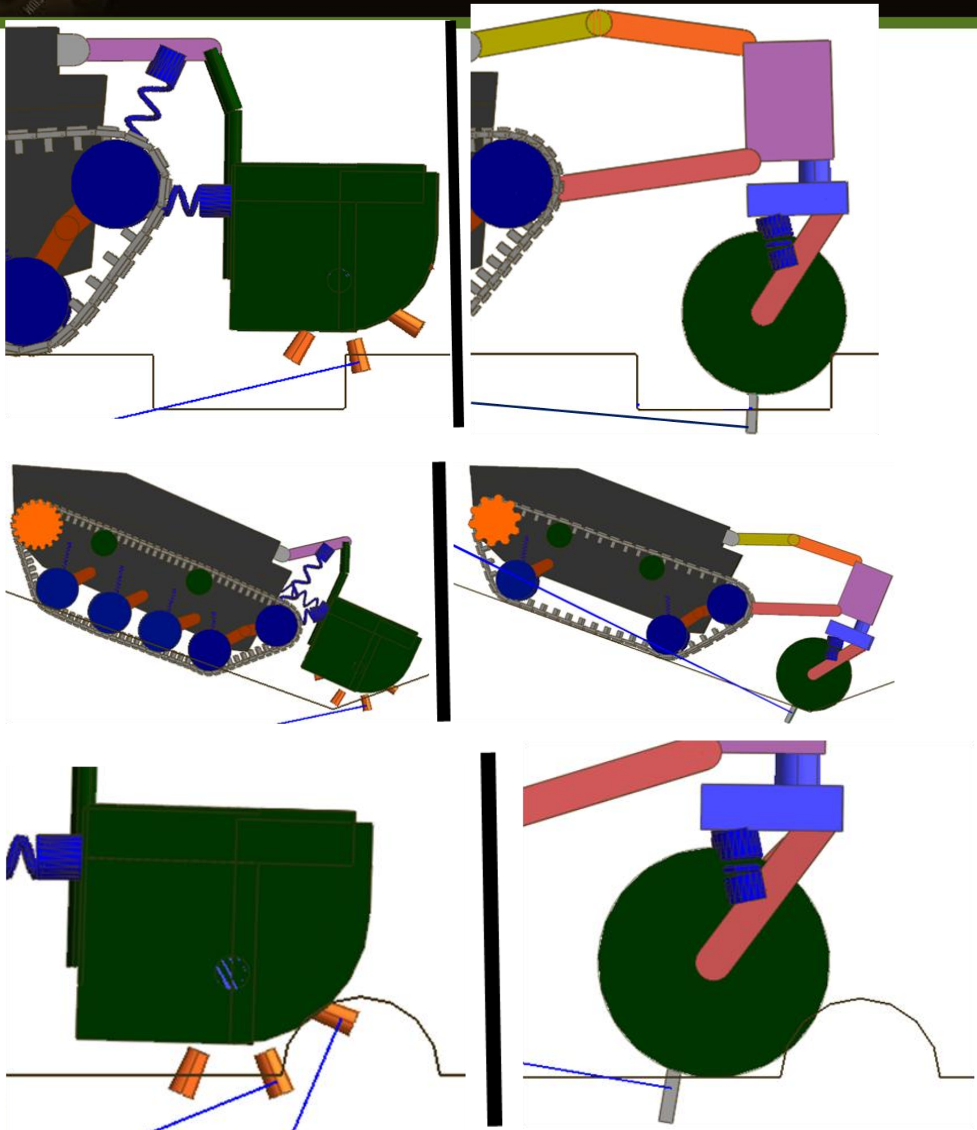


- Average peak interface loads with Flail over pot hole event:
  - 3395 N with 4 road wheels
  - 3750 N with 2 road wheels
- Peak acceleration magnitude at chassis over pothole:
  - 1.76 g’s with 4 road wheels
  - 2.09 g’s with 2 road wheels
- Performance on grades:
  - 2 road wheels: 60% with flail over sand, 45% over clay
  - 4 road wheels: 55% with flail over sand, 55% over clay

Roller vs. Flail Loads Comparison



- Average peak interface loads higher with roller in all cases.

Event	Average of Peak Interface Loads [N]	
	Flail	Roller
Half Round	4405	8224
Pothole	3572	11545
Vditch	3229	5041

- Average magnitude of forces over cross country:
  - Flail: 1761N; Roller: 1980 N

Band vs. Segmented Track

- Surrogate band track modeled had slight improvement in average chassis vibration magnitudes
  - Band Track: 0.36 g’s; Segmented Track: 0.42 g’s
- Care must be taken – 90 segments may lead to higher frequency vibrations
  - Not realistic of actual band track

Sensitivity Study

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- Sensitivity study performed varied single parameter
  - Half round event, without any implement, over clay, with 4 road wheels per side

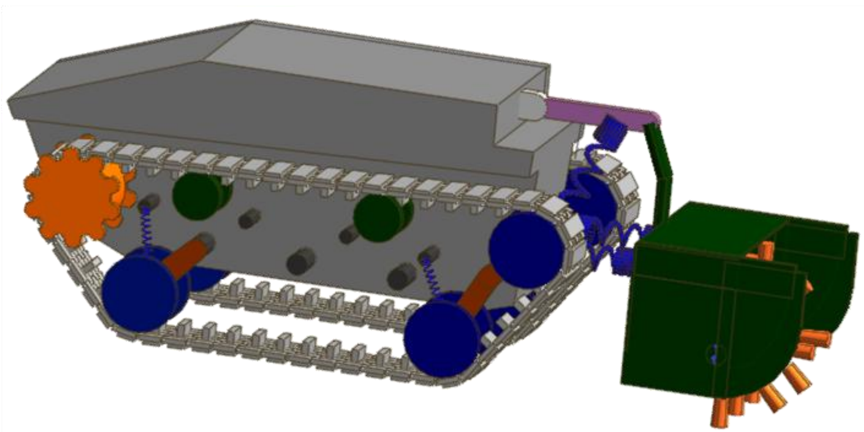
Design Sensitivity	% Change of values	Configuration Tested
Initial Track Bushing Tension / Preload	25 – 100 – 400	Segmented Track
Band Track Material Properties (Youngs Modulus)	50 – 100 – 200	Band Track
Backing Pad - Road Wheel Contact Stiffness	50 – 100 – 200	Segmented Track

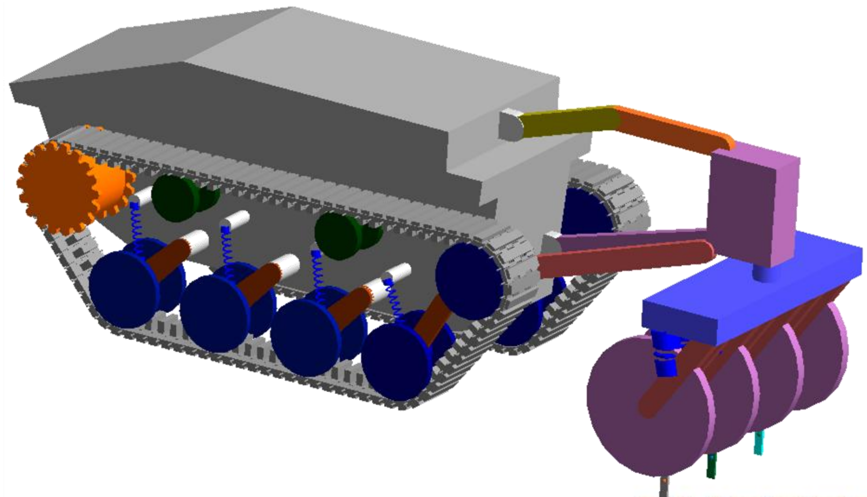
Sensitivity Results

- Segmented Track Bushing Preload: 125 N – 500 N – 2000 N
  - Increasing the bushing preload increased the peak chassis acceleration magnitude
- Band Track Material Properties – Young's Modulus: 23.5 MPa – 47 MPa – 94 MPa
  - Increasing the Young's Modulus increases the peak chassis acceleration magnitude
- Segmented Track Backing Pad and Road Wheel Contact Stiffness: 1751 kN/m – 3502 kN/m – 7005 kN/m
  – Increasing the contact stiffness increases the peak chassis acceleration magnitude

Conclusion

- Configuration with 4 road wheels per side, band track, with the flail had lower interface loads and chassis accelerations overall
- Innovative terramechanics application of rake shearing and hammer impact





BACKUP

Notional Vehicle Parameters

Constant Design Parameter	**Value**
Chassis Mass	450 kg
Overall Length (less implement)	2.1 m
Overall Width (less implement)	1 m
Wheelbase	1.13 m
Vehicle Track Width	0.746 m
Width of Individual Tracks	0.203 m
Chassis Roll Inertia	35.80 kg-m^2
Chassis Pitch Inertia	134.01 kg-m^2
Chassis Yaw Inertia	127.14 kg-m^2
Sprocket Carrier Radius	0.14 m
Road Wheel & Idler Radii	0.14 m

Sensitivity Results

Bushing Preload (N)	Peak Chassis Acceleration Magnitude [g]
500	1.34
125	1.31
2000	1.37

Young's Modulus [Mpa]	Radial "Bushing" Stiffness [kN/m]	Peak Chassis Acceleration Magnitude [g]
47	5618	1.56
23.5	1433	1.36
94	11235	1.67

Track-Road Wheel Contact Stiffness (kN/m)	Peak Chassis Accelerations [g]
3502	1.34
1751	1.28
7005	1.57